Implications of the CDMS result on Dark Matter and LHC physics

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The requirements of electroweak symmetry breaking (EWSB) and correct thermal relic density of Dark Matter (DM) predict large DM spin-independent direct detection cross section in scalar DM models based on $SO(10)$ non-supersymmetric GUTs. Interpreting the CDMS signal events as DM recoil on nuclei, we study implications of this assumption on EWSB, Higgs boson mass and direct production of scalar DM at LHC experiments. We show that this interpretation indicates relatively light DM, $M_{\rm DM} \sim \mathcal{O}(100)$ GeV, with large pair production cross section at LHC in correlation with the spin-independent direct DM detection cross section. The next-to-lightest dark scalar $S_{\rm NL}$ is predicted to be long-lived, providing distinctive experimental signatures of displaced vertex of two leptons or jets plus missing transverse energy.

Introduction. The existence of cold dark matter (DM) of the Universe is firmly established by cosmological observations [1]. Because the standard model (SM) of particle interactions does not contain a cold DM candidate, its existence is a clear signal of new physics beyond the SM. However, the origin, nature and properties of the DM have so far remained completely unknown.

The Cryogenic Dark Matter Search (CDMS II) at Soudan mine has recently observed two weakly interacting massive particle (WIMPs) recoil candidate events on nuclei in the signal region [2] and additional two events just outside the signal region border [3]. All the events have recoil energy between 12-15 keV. Although statistically inconclusive, CDMS Collaboration cannot reject the events as a signal of DM scattering on nuclei [3]. In that case the CDMS II result has important implications on DM theory as well as on DM direct detection at colliders.

Any theory beyond the SM that attempts to explain the CDMS II result must, in the first place, explain what is the WIMP, why it is stable, and to predict correct cosmological DM density together with phenomenologically acceptable DM mass scale. After answering those questions one can address phenomenological implications of the CDMS II result on other experiments.

It is plausible that the stability of WIMP is due to a discrete Z_2 symmetry which is an unbroken remnant of some underlying $U(1)$ gauge group [4]. This possibility is particularly attractive because it suggests a Grand Unified Theory (GUT) gauge group with a larger rank than that of $SU(5)$ [5]. It was shown in Ref. [6] that if the underlying GUT gauge group is $SO(10)$ [7], the argument of [4] predicts that minimal non-supersymmetric DM must be embedded into scalar representation **16** due to the generated matter parity $P_M = (-1)^{3(B-L)}$. In this scenario the DM and its stability mechanism, non-vanishing neutrino masses via the seesaw mechanism [8] and the baryon asymmetry of the Universe via leptogenesis [9] all spring from the same source – the breaking of $SO(10)$ gauge symmetry.

The low energy phenomenology of this GUT scenario is very rich and predictive. The DM must consist of dark scalar singlet(s) S [10] and doublet(s) H_2 [11], thus non-supersymmetric $SO(10)$ GUT represents an ultraviolet completion of those scalar DM models [6, 12, 13]. The GUT scale boundary conditions, together with the requirements of vacuum stability and perturbativity of scalar self-couplings, strongly constrain the allowed parameter space of the theory. Instead of postulating a negative Higgs μ_1^2 as in the SM, the electroweak symmetry breaking (EWSB) can be dynamically induced by the Higgs boson interaction with dark scalars either via renormalization group (RG) evolution of μ_1^2 from the GUT scale $M_{\rm G}$ to M_Z [12] as in supersymmetric theories [14], or via DM 1-loop contributions to the Higgs boson effective potential [15, 16], representing a realistic example of the Coleman-Weinberg idea [17]. Requiring successful radiative EWSB and the observed amount of DM produced in thermal freeze-out, the scenario predicts the DM spin-independent direct detection cross section to be just at the CDMS II experimental sensitivity.

In this work we argue that CDMS II may have observed the scalar DM recoils on ordinary matter and study implications of this fact on the DM direct production processes at the Large Hadron Collider (LHC) experiments at CERN. Because of the low recoil energy of all the CDMS events, consistency of CDMS data may indicate relatively light DM detectable at the LHC. We improve the Higgs boson effective potential at 1-loop level and require radiative EWSB via renormalization effects. We calculate the generated thermal relic DM density and spin-independent direct detection cross section of DM scattering on nuclei and show that the new CDMS II data prefers light Higgs boson in agreement with the precision data analyses [18]. For the obtained parameter space we study the production and decays of dark scalar particles at LHC. Most importantly for the LHC phenomenology, we show that this scenario *predicts* long lifetime for the next-to-lightest (NL) neutral dark scalar particle. Decays of the NL dark scalar provide an unique experimental signature of displaced vertex in di-lepton and di-quark signal

occurs in the the decays $S_{\rm NL} \to S_{\rm DM}\ell^+\ell^-$, $S_{\rm DM}q\bar{q}$. This signature allows one to discriminate the dark scalar processes over the SM background and to discover and test light scalar DM at the LHC.

The minimal $SO(10)$ scalar DM scenario. The minimal scalar DM scenario [12] contains the SM Higgs in a scalar representation **10** and the DM in a scalar **16** of $SO(10)$. Below the $M_{\rm G}$ and above the EWSB scale the model is described by the $H_1 \to H_1$, $S \to -S$, $H_2 \to -H_2$ invariant scalar potential

$$\begin{aligned}
V &= \mu_1^2 H_1^\dagger H_1 + \lambda_1 (H_1^\dagger H_1)^2 + \mu_2^2 H_2^\dagger H_2 + \lambda_2 (H_2^\dagger H_2)^2 \\
&+ \mu_S^2 S^\dagger S + \frac{\mu_S'^2}{2}\left[S^2 + (S^\dagger)^2\right] + \lambda_S (S^\dagger S)^2 \\
&+ \frac{\lambda_S'}{2}\left[S^4 + (S^\dagger)^4\right] + \frac{\lambda_S''}{2}(S^\dagger S)\left[S^2 + (S^\dagger)^2\right] \\
&+ \lambda_{S1}(S^\dagger S)(H_1^\dagger H_1) + \lambda_{S2}(S^\dagger S)(H_2^\dagger H_2) \\
&+ \frac{\lambda_{S1}'}{2}(H_1^\dagger H_1)\left[S^2 + (S^\dagger)^2\right] + \frac{\lambda_{S2}'}{2}(H_2^\dagger H_2)\left[S^2 + (S^\dagger)^2\right] \\
&+ \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\
&+ \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + (H_2^\dagger H_1)^2\right] \\
&+ \frac{\mu_{SH}}{2}\left[S^\dagger H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\mu_{SH}'}{2}\left[S H_1^\dagger H_2 + \text{h.c.}\right],
\end{aligned} \tag{1}$$

together with the GUT scale boundary conditions

$$\begin{aligned}
\mu_1^2(M_{\rm G}) > 0,\ \mu_2^2(M_{\rm G}) = \mu_S^2(M_{\rm G}) > 0, \\
\lambda_2(M_{\rm G}) = \lambda_S(M_{\rm G}) = \lambda_{S2}(M_{\rm G}),\ \lambda_3(M_{\rm G}) = \lambda_{S1}(M_{\rm G}),
\end{aligned} \tag{2}$$

and

$$\begin{aligned}
\mu_S'^2,\ \mu_{SH}^2 \lesssim \mathcal{O}\left(\tfrac{M_{\rm G}}{M_{\rm P}}\right)^n \mu_{1,2}^2, \\
\lambda_5,\ \lambda_{S1}',\ \lambda_{S2}',\ \lambda_S'' \lesssim \mathcal{O}\left(\tfrac{M_{\rm G}}{M_{\rm P}}\right)^n \lambda_{1,2,3,4}.
\end{aligned} \tag{3}$$

While the parameters in Eq. (2) are allowed by $SO(10)$, the ones in Eq. (3) can be generated only after $SO(10)$ breaking by operators suppressed by n powers of the Planck scale $M_{\rm P}$.

The neutral components of dark bosons yield the scalar mass eigenstates $S_{\rm R1}$ and $S_{\rm R2}$, and the pseudoscalar ones $S_{\rm I1}$ and $S_{\rm I2}$ with the mass spectrum $M_{\rm I1} \le M_{\rm R1} < M_{\rm I2} \le M_{\rm R2}$, (or I$\leftrightarrow$R) where $S_{\rm I1}$, $S_{\rm R1}$ and $S_{\rm I2}$, $S_{\rm R2}$ are almost degenerate in mass due to the smallness of the parameters in Eq. (3). For clarity we denote the DM particle by $S_{\rm DM}$ and the NL scalar by $S_{\rm NL}$.

We stress that the mass degeneracy of $S_{\rm DM}$ and $S_{\rm NL}$ is a generic *prediction* of the scenario and follows from the underlying $SO(10)$ gauge symmetry via Eq. (3). This degeneracy has several phenomenological implications which allow to discriminate this scenario from other DM models. First, it implies long lifetime for $S_{\rm NL}$ which provides clear experimental signature of displaced vertex in the decays $S_{\rm NL} \to S_{\rm DM}\ell^+\ell^-$ at the LHC. We study this experimental signature in this work. Second, it offers a possibility to reconcile the DAMA/NaI and DAMA/LIBRA annual modulation signal [19] with the results of XENON10 [20] and CDMS II [2] experiments via the idea of inelastic DM scatterings [21]. The inelastic DM requires degenerate mass states as predicted by (3). While spin-dependent inelastic scatterings may explain all the data [22], the spin-independent DM scatterings as a solution to DAMA signal is (almost) excluded by XENON10 and CDMS II results [23], and we do not pursue this possibility here.

At $M_{\rm G}$ the SM gauge symmetry is not spontaneously broken, $\mu_1^2(M_{\rm G}) > 0$. To obtain EWSB at low energies we require that $\mu_1^2(M_Z)$ becomes negative by RG evolution [12] which is the only possibility in the case of light DM. We RG improve [24] our previous calculation with 1-loop corrections to the effective potential as described in [15].

DM direct detection and Higgs boson mass. In our scenario both the DM annihilation at early Universe and the DM scattering on nuclei are dominated by tree level SM Higgs boson exchange. The relevant DM-Higgs effective coupling is

$$\lambda_{\rm eff}\, v = \frac{1}{2}(\sqrt{2}s\, c\, \mu_{SH}' - 2s^2(\lambda_3 + \lambda_4)v - 2c^2\lambda_{S1}v), \tag{4}$$

where s, c are the sine, cosine of the singlet-doublet mixing angle. We systematically scan over the full parameter space of the model by iterating between $M_{\rm G}$ and M_Z using RGEs of Ref. [12]. We require successful dynamical EWSB and calculate the thermal freeze-out DM abundance and spin-independent direct detection cross section per nucleon using MicrOMEGAS package [25]. The latter is approximately given by

$$\sigma_{\rm SI} \approx \frac{1}{\pi} f_N^2 \left(\frac{\lambda_{\rm eff} v}{v M_{\rm DM}}\right)^2 \left(\frac{M_N}{M_h}\right)^4, \tag{5}$$

where $f_N \approx 0.47$ is the nucleonic form factor that includes all contributions from the valence and sea quarks (s-dominated) and gluons.

We present in Fig. 1 our prediction for the spin-independent DM cross section as a function of DM mass for different Higgs boson masses described by the colour code 130 GeV $< M_h <$ 180 GeV from yellow to violet. The present experimental bounds on $\sigma_{\rm SI}$ (solid lines) [2, 20] together with the expected sensitivities (dashed lines) are also shown. For every point we require the WMAP 3σ result $0.094 < \Omega_{\rm DM} < 0.129$. For the high mass points, $M_{\rm DM} > 700$ GeV, EWSB is obtained radiatively via effective potential due to large "soft" portal coupling μ_{SH}' [15]. This parameter region cannot be directly tested at the LHC. In the low mass region, 180 GeV $< M_{\rm DM} <$ 700 GeV, EWSB occurs due to renormalization of μ_1^2 from $M_{\rm G}$ to M_Z. The lower bound on the DM mass comes from the top quark loop contributions to the SM Higgs boson effective potential. The low mass points in Fig. 1 with small $\sigma_{\rm SI}$ are due to cancellations between the parameters in Eq. (4). If the CDMS

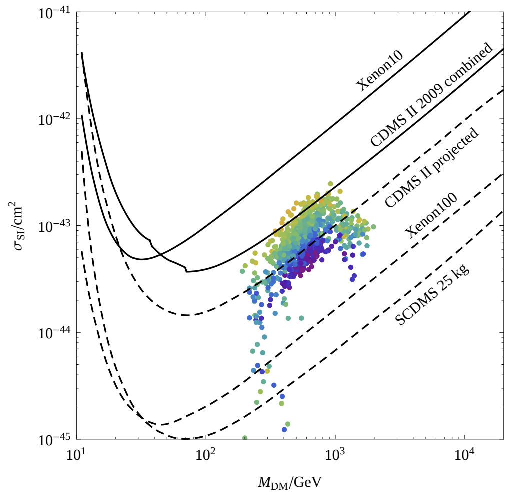

Figure 1: DM direct detection cross-section/nucl. *vs.* $M_{\rm DM}$. Color shows SM Higgs boson masses from 130 GeV (yellow) to 180 GeV (violet). Solid lines represent current bounds, dashed lines are expected future sensitivities.

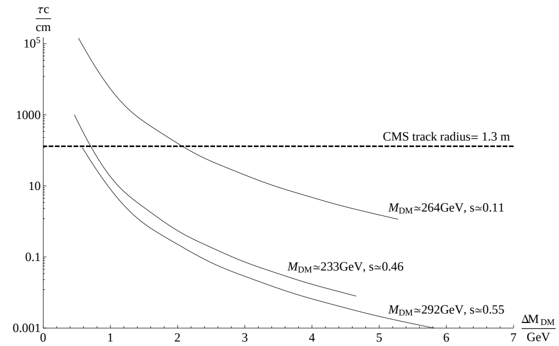

Figure 2: Distance of DM displaced vertex from the interaction region at LHC experiments as a function of $\Delta M_{\rm DM}$. Examples for three data points with different values of DM mass $M_{\rm DM}$ and sine of the mixing angle s are show. The dashed line is the CMS tracker radius [26].

II events [2] indeed are DM recoil, those points are excluded. Fig. 1 clearly prefers light Higgs boson to increase the spin-independent cross section (5) to explain the CDMS II events.

LHC phenomenology. The main parton level production processes for the dark sector scalars at the LHC are $q\bar{q} \to H^+H^-$, $gg \to S_{\rm DM,NL}S_{\rm DM,NL}$, $q\bar{q}' \to S_{\rm DM,NL}H^\pm$ and $q\bar{q} \to S_{\rm NL}S_{\rm DM}$, followed by the decays $S_{\rm NL} \to S_{\rm DM}\ell^+\ell^-$, $S_{\rm NL} \to S_{\rm DM}q\bar{q}$ and $H^+ \to S_{\rm DM}q\bar{q}$, $H^+ \to S_{\rm DM}\ell\bar{\nu}$. Although the pair production H^+H^- is the least model dependent process due to the virtual γ, Z exchange, the cleanest experimental signature is provided by the $S_{\rm NL}$ decays. Since the DM and the NL scalar are almost degenerate in mass, the mean lifetime τ of NL scalar can be long and $S_{\rm NL}$ can travel macroscopic distances before decaying. Therefore the decays $S_{\rm NL} \to S_{\rm DM}\ell^+\ell^-$, $S_{\rm DM}q\bar{q}$ can be tagged by the displaced vertex of lepton or jet pairs and missing transverse energy $\not{E}_{\rm T}$, providing SM background free signal of scalar DM at the LHC.

In Fig. 2 we plot the distance $c\tau$ of the displaced vertices from the interaction region as a function of the mass splitting $\Delta M_{\rm DM} = M_{\rm NL} - M_{\rm DM}$ for three examples of DM mass and mixing. Depending on the mass gap and the mixing angle, the displacement can range from micrometers to several meters. In the case of such a *far* displaced vertex, the experimental signatures of the $S_{\rm NL}S_{\rm NL}$ final state are $\ell\ell\ell\ell$, $jjjj$, $\ell\ell jj$ with displaced $\ell\ell$ or jj vertices and the missing $\not{E}_{\rm T}$. The decays with $\nu\nu$ final states are completely invisible, but those make up roughly 20% of the total $S_{\rm NL}$ branching fraction depending on $\Delta M_{\rm DM}$. Therefore we predict high efficiency in the detection of NL scalar decays at the LHC.

We have computed the $S_{\rm NL}S_{\rm NL}$, $S_{\rm DM}S_{\rm DM}$, $S_{\rm DM}S_{\rm NL}$ and H^+H^- production cross sections $\sigma_{\rm LHC}$ in pp collisions at LHC by convoluting over the parton distribution function of Ref. [27]. We note that the production processes are similar to those of the Inert Doublet model studied in [28], but the dependence on model parameters is very different in our case.

In Fig. 3 we show the cross sections for these processes for the collision energy $\sqrt{s} = 14$ TeV as a function of DM mass for *the same points* as in Fig. 1. The colour code is explained in the caption. Because $S_{\rm DM}$ and $S_{\rm NL}$ are almost degenerate, their production cross sections are almost equal. Because the DM particle is neutral, the H^+ cross section exceeds the $S_{\rm DM}$ and $S_{\rm NL}$ ones. The cross sections fall rapidly with outgoing particle masses. Taking into account the visible branching fractions as described above, DM can be discovered at the LHC for $M_{\rm DM} < \mathcal{O}(300)$ GeV.

Comparison of Fig. 1 and Fig. 3 reveals correlation between the low $M_{\rm DM}$ points with accidentally small $\sigma_{\rm SI}$ in Fig. 1 and the ones with small $\sigma_{\rm LHC}$ in Fig. 3. Interpreting the CDMS II events as the DM recoil excludes the small cross sections regions. Therefore the CDMS II result implies large DM production cross section at LHC provided DM mass is below $M_{\rm DM} < \mathcal{O}(300)$ GeV. The recoil energy 12-15 keV of the CDMS events puts a lower bound on the DM mass, $M_{\rm DM} > \mathcal{O}(10)$ GeV. Clearly the consistency of recoil energy of all the CDMS II events does not exclude the possibility of heavy DM but it favours light DM, $M_{\rm DM} \sim \mathcal{O}(100)$ GeV. Therefore, if the observed CDMS events really are due to DM recoils, our results show that scalar DM can be directly discovered at the LHC.

Conclusions. We have considered implications of the recent CDMS II data on the minimal scenario of $SO(10)$ scalar DM. The parameter space of the model is strongly constrained by the requirements of vacuum stability, perturbativity, correct DM density and dynamical EWSB via DM interactions, *cf.* Fig. 1. If we assume that the ob-

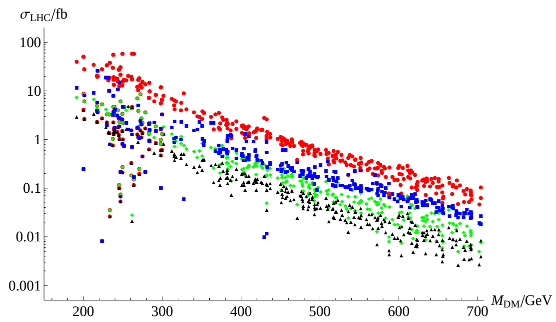

Figure 3: Direct production cross-section of $pp \to H^+H^-$ (red), $pp \to S_{\rm DM,NL}S_{\rm DM,NL}$ (blue), $pp \to S_{\rm DM,NL}H^\pm$ (green) and $pp \to S_{\rm NL}S_{\rm DM}$ (black) at the LHC for $\sqrt{s} = 14$ TeV.

served signal events in the CDMS II experiment were DM recoil on nuclei, the recoil energy and the position of the highest sensitivity region for the CDMS II suggest a light DM with large spin-independent cross section, which implies large DM production cross section at the LHC. The distinctive collider signature of this scenario is a highly displaced vertex of two leptons or jets and missing transverse energy. The Higgs boson must be light to explain the CDMS II observations.

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